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Focus paper

An Andean tectonic cycle: From crustal thickening to extension in a thin crust (34°–37°SL)

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A B S T R A C T

Several orogenic cycles of mountain building and subsequent collapse associated with periods of shallowing and steepening of subduction zones have been recognized in recent years in the Andes. Most of them are characterized by widespread crustal delamination expressed by large calderas and rhyolitic flare-up produced by the injection of hot asthenosphere in the subduction wedge. These processes are related to the increase of the subduction angle during trench roll-back. The Payenia paleoflat-slab, in the southern Central Andes of Argentina and Chile (34°–37°S) recorded a complete cycle from crustal thickening and mountain uplift to extensional collapse and normal faulting, which are related to changes in the subduction geometry. The early stages are associated with magmatic expansion and migration, subsequent deformation and broken foreland. New ages and geochemical data show the middle to late Miocene expansion and migration of arc volcanism towards the foreland region was associated with important deformation in the Andean foothills. However, the main difference of this orogenic cycle with the previously described cycles is that the steepening of the oceanic subducted slab is linked to basaltic flooding of large areas in the retroarc under an extensional setting. Crustal delamination is concentrated only in a narrow central belt along the cordilleran axis. The striking differences between the two types of cycles are interpreted to be related to the crustal thickness when steepening the subducting slab. The crustal thickness of the Altiplano is over 60–80 km, whereas Payenia is less than 42 km in the axial part, and near 30 km in the retroarc foothills. The final extensional regime associated with the slab steepening favors the basaltic flooding of more than 8400 km^3 in an area larger than 40,000 km^2, through 800 central vents and large fissures. These characteristics are unique in the entire present-day Andes.

1. Introduction

Andean-type tectonics has been considered a simple setting where subduction of oceanic crust generates the formation of a magmatic arc, which leads to the thermal weakening of the crust, and produces a subsequent thickening in a compressive regime (Ramos et al., 1996; Kley et al., 1999; Cobbold and Rossello, 2003). Recent researches have shown that this scenario is much more complex, where compression and extension alternate and are controlled by the absolute motion of the South American continent (Silver and Russo, 1996; Ramos, 1999; Collins, 2002; Oncken et al., 2006; Boekhout et al., 2012). This fact clearly explains a large period of subduction where trench retreats during the opening of the South Atlantic Ocean, associated with negative trench roll-back velocity in the upper plate, which generates extension (Ramos, 2010). This episode alternates with periods of positive roll-back when the upper plate overrides the trench and compression dominates through the margin. The westwards motion of the upper plate and the overriding of the trench begun after the break-up of Western Gondwana and separation of Africa (Somoza and Zaffarana, 2008). However, detailed examination of different Andean segments has shown alternating regimes superimposed on these first order episodes (Mpodozis and Ramos, 1990, 2008). For example, in southern Peru and northern Argentina changes in the geometry of the Benioff zone can explain important crustal thickening and foreland fold and thrust belt deformation, subsequent

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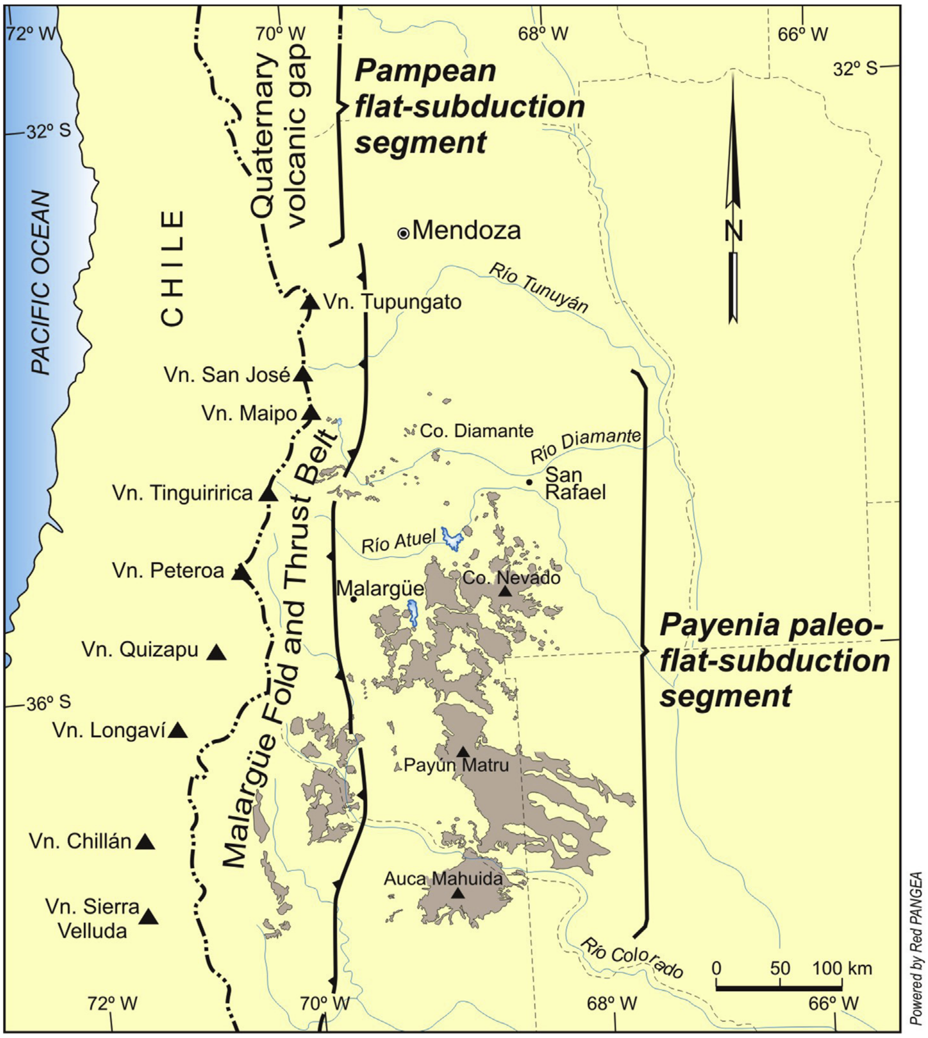

Figure 1. Location of the study segment of the southern Central Andes. The Payenia paleo-flat-slab subduction segment matches the active volcanic arc between the Tupungato and Sierra Velluda volcanoes. Note the position of the Malargüe fold and thrust belt and the extent of basaltic floods from north of Cerro Diamante to Auca Mahuida plateau (modified from Ramos and Folguera, 2011).

crustal delamination, and rhyolitic ignimbrite flare-up associated with localized extension (Kay et al., 1994; Allmendinger et al., 1997; James and Sacks, 1999; Kay et al., 1999; de Silva and Gosnold, 2007; Saylor and Horton, 2014). In these cases the initial thick crust (Isacks, 1988) favored generalized delamination of the lower crust and the lithospheric mantle during steepening of the subduction zone associated with voluminous rhyolitic ignimbrite eruptions as the Altiplano-Puna Volcanic Complex (Kay and Coira, 2009; Ramos, 2009).

In the southern Central Andes of Mendoza and northern Neuquén (34°–37°S) (Fig. 1) recent field work, geochronological data, and petrological studies have shown a distinct pattern in the interaction between timing of deformation, type of volcanic activity, and changes in the tectonic regime. This pattern is linked to an original normal-to-thin crust in the main Andes and huge and extensive basaltic floods in the retroarc foreland region.

The objective of this paper is to present new data on the timing of expansion of the arc volcanism, its main geochemical characteristics, and the structural evolution of the region to better understand the geological processes that lead to a complete tectonic cycle of mountain building. This cycle started with a normal-thick crust associated with calcalkaline stratovolcanoes along the main axis of the Andes, followed by deformation, crustal thickening and expansion of the arc magmatism towards the foreland (Spagnuolo et al., 2012a). Subsequent retreat toward the trench of the arc volcanic rocks is linked to generalized extension and intraplate voluminous foreland basalts. Coeval eruptions of rhyolitic domes, calderas and flows were restricted along the axis of the Andes. This volcanism is followed by a new cycle of arc magmatism in a series of stratovolcanoes which are associated with deformation along the main Andes. These stratovolcanoes erupted again on a normal-thick crust that marks the beginning of a new cycle.

2. Geological setting

The geological framework of this segment of the southern Central Andes between 34° and 37°S is characterized by the low elevation of the Cordillera de la Costa (<1000 m a.s.l.) and the Cordillera Principal (<3000 m, if the Quaternary volcanoes are excluded), in comparison with the segment located immediately to the north, where the Frontal and Principal cordilleras exceed 6900 m. The main Andes at these latitudes were uplifted as a result of the Miocene contraction of the Malargüe fold and thrust belt. This belt involved basement blocks characterized by Permian and

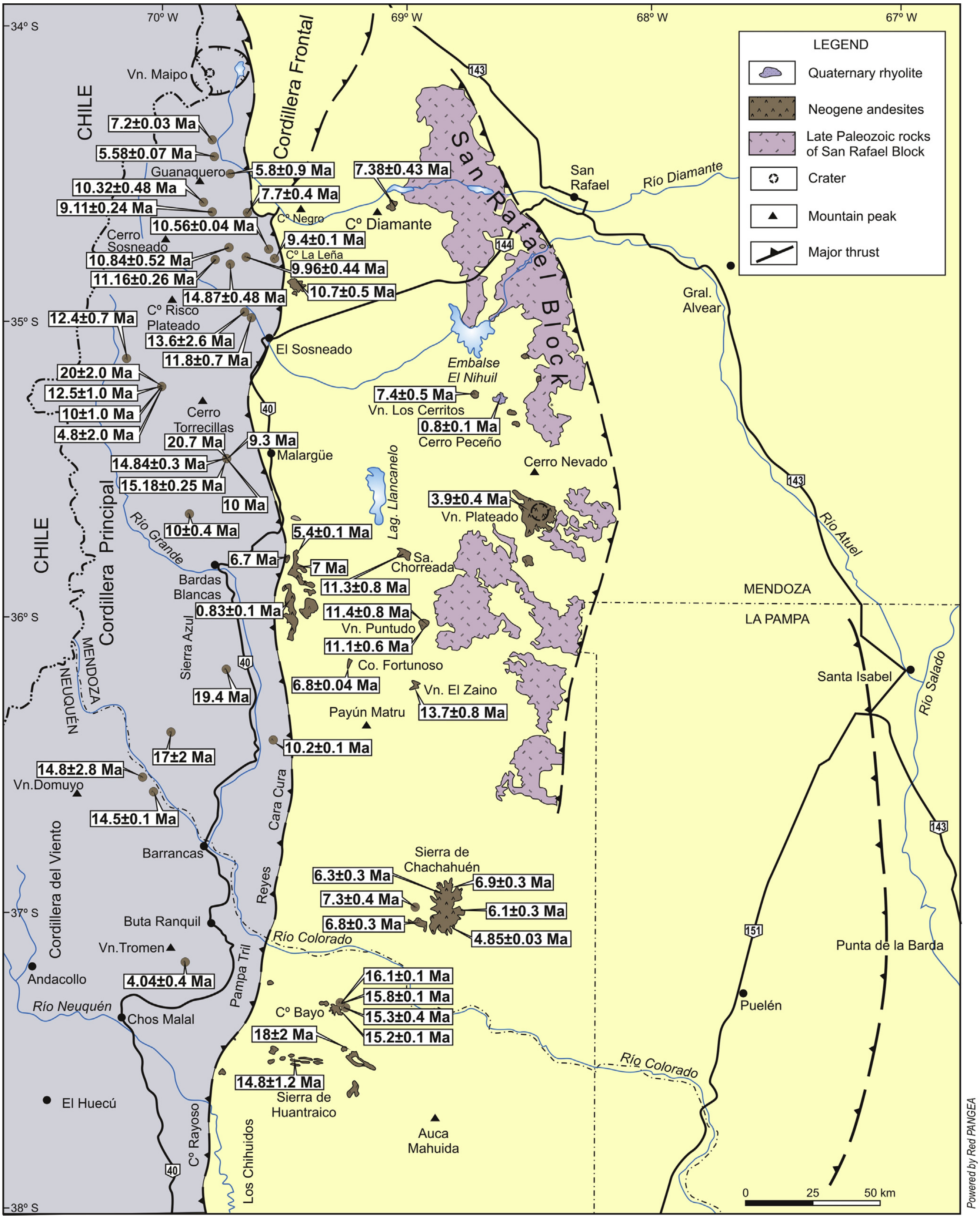

Figure 2. Expansion of the Neogene arc volcanic rocks recorded in the foreland region in southern Mendoza and northern Neuquén (based on Ramos and Folguera, 2005; Ramos and Kay, 2006). Note that present volcanic arc is further west along the Chilean slope of the Cordillera Principal. Miocene ages based on Ramos and Barbieri (1989), Ostera et al. (1999), Nullo et al. (2002), Cobbold and Rossello (2003), Kay et al. (2006a, b), Giambiagi et al. (2008), Silvestro and Atencio (2009), Gudnason et al. (2012), Spagnuolo et al. (2012a) and this study (shown in Table 1).

Figure 3. Examples of calcalkaline volcanic centers in the foreland of southern Mendoza partially dismantled by erosion: Diamante, 7.38 ± 0.43 Ma; El Zaino, 13.7 ± 0.8 Ma; Sierra Chorreada, 11.3 ± 0.8 Ma; Cerro Puntudo, 11.4 ± 0.8 Ma (location in Fig. 2).

Triassic volcanic rocks, covered by Jurassic and Cretaceous deposits, which contrasts with the dominant thin-skinned deformation of the Andes further north in the Aconcagua region (Kozlowski et al., 1993; Ramos et al., 1996; Giambiagi and Ramos, 2002; Giambiagi et al., 2008).

The studied southern Central Andean segment is located immediately to the south of the Pampean flat-slab characterized by absence of Quaternary arc volcanic rocks (Jordan et al., 1983a; Ramos et al., 2002). Since the early studies of this segment it has been evident that one of the outstanding features is the presence of basaltic plateaux developed in the foreland during Quaternary times (Jordan et al., 1983b). The presence of this basaltic plateau is exceptional in the entire Andean foreland, covering an area over 40,000 km^2 (Muñoz and Stern, 1988; Ramos and Kay, 2006; Folguera et al., 2009; Ramos and Folguera, 2011).

The study segment is characterized by widespread volcanic sequences that in the Cenozoic covered most of the retroarc region as far as 550 km away from the trench (Bermúdez et al., 1993; Kay, 2001; Ramos and Kay, 2006). This expansion and migration of the arc volcanism were associated with a wave of foreland deformation. A subsequent retreat of the arc volcanism was followed by extension across the entire foreland and associated with poorly evolved basalt-flows.

3. The magmatic rocks

Based on the age, geochemical, and isotopic characteristics of these volcanic rocks, three different suites can be recognized, a calcalkaline suite associated with the volcanic arc front and its subsequent expansion; an intraplate basaltic province in the foreland, and a series of rhyolitic calderas along the main Andes.

3.1. *The Miocene arc rocks*

It is well established through the studies of Charrier et al. (2005) that during Oligocene to early Miocene times a large volcano-tectonic rift zone was developed along a western volcanic belt through the Chilean slope of the Cordillera Principal. These sequences grouped in the Coya Machalí Formation are a voluminous basaltic to rhyolitic volcanic and sedimentary complex composed of volcanic flows, agglomerates, lithic tuffs, and volcaniclastic and lacustrine sedimentary rocks, locally up to 1300 m thick. This western volcanic belt is bounded by normal faults and its age is constrained by K-Ar dates that range from 27.7 Ma to 20.5 Ma (Charrier et al., 2005).

The Oligocene Coya Machalí volcanic rocks between 32° and 35°S are heavily deformed and unconformably covered by the calc-alkaline sequence of the Farellones Formation and equivalent units (Vergara et al., 1988). This unit is up to 2400 m thick and ranges in age between 21 and 16 Ma (Charrier et al., 2007). South of 35°S the Miocene volcanic belt is mainly exposed in the Argentine slope of the Cordillera Principal as seen in the map of Fig. 2.

The Miocene arc volcanic rocks are expanded to the east and range in age from 20 Ma up to 10 Ma in the foothills (Nullo et al., 2002; Giambiagi et al., 2008; Sruoga et al., 2008; Spagnuolo et al., 2012a). The characteristics of these calcalkaline rocks in the oldest terms indicate a transition between tholeiitic to more evolved

Table 1
New K-Ar ages of the calc-alkaline volcanic rocks from the Payenia[a].

Sample and Loc.	Material	% K	Ar. Rad. nl/g	% Ar. Atmosphere	Age (Ma)	Error 2σ
Cerro El Zaino (andesite) 36°06′13.5″S 68°48′54.0″W	Whole rock	1.166	0.624	60	13.7	±0.8
Cerro Puntudo (dacite)	Amphibole	0.996	0.442	67	11.4	±0.8
Cerro Puntudo (dacite)	Plagioclase	0.402	0.175	86	11.2	±1.4
Cerro Puntudo (dacite) 35°56′38.0″S 68°45′11.6″W	Plagioclase	0.402	0.173	58	11.7	±0.7
Plagioclase average age					11.1	±0.6
Cerro Chorreado (andesite)	Plagioclase	0.481	0.210	83	11.2	±1.3
Sierra Chorreada (andesite) 35°44′43.0″S 68°50′50.5″W	Plagioclase	0.481	0.213	72	11.3	±1.0
Plagioclase average age					11.3	±0.8
Cerro Plateado (dacite)	Plagioclase	0.395	0.058	79	3.8	±0.5
Cerro Plateado (dacite) 35°44′40.5″S 68°28′56.0″W	Plagioclase	0.395	0.064	88	4.1	±0.8
Plagioclase average age					3.9	±0.4
Cerro Los Cerritos (andesite) 35°16′51.9″S 68°44′13.3″	Amphibole plagioclase	0.819	0.238	68	7.4	±0.5
Cerro Peceño (rhyolite) 35°17′30–7″S 68°37′56.6″W	Whole rock	3.571	0.104	61	0.8	±0.1
	Whole rock	3.571	0.100	86	0.7	±0.2
	Average age				0.8	±0.1
Cerro Diamante (andesitic basement) 34°37.439′S 69°4.428′W		1.49			7.38	±0.43

[a] Dates obtained in the Geochronological Laboratory of the SERNAGEOMIN by K/Ar in different minerals and whole rock.

rocks as pointed out by Sruoga et al. (2008) and Spagnuolo et al. (2012a).

Several exposures of hornblende-bearing andesites located east of the orogenic front north of 37°S latitude in the southern sector of the Mendoza Province were traditionally considered as part of the Mollelitense by Groeber (1947) and therefore considered as Paleogene in age. However, the geochronological dating of the calcalkaline sequences in Sierra de Huantraico, located east of the orogenic front in the foreland, indicated the occurrence of middle Miocene arc volcanic rocks in northern Neuquén (Ramos and Barbieri, 1989; Kay et al., 2006a) (see Fig. 2). Further north the work of Kay et al. (2006b) shows late Miocene andesites and dacites in Chachahuén, southern Mendoza, confirming the expansion of the magmatism proposed by Bermúdez et al. (1993).

3.1.1. New geochronological data

In order to recognize the extent of this Miocene volcanism in the foreland, a detail reconnaissance of all the important andesitic to dacitic calcalkaline volcanic centers was done north of the Chachahuén volcano. They are exhumed volcanoes, partially eroded, such as El Zaino, Puntudo, Chorreado, Plateado, Los Cerritos, and Diamante were surveyed and sampled (Fig. 3). Most of the analyzed rocks according to the petrographic analyses vary from dacites to andesites. The only exception was the Cerro Peceño, which consists of an isolated small dome composed of a welded rhyolitic ignimbrite that was sampled (see Table 1). The Cerro Zaino is formed by some hornblende-bearing andesite with abundant plagioclase and scarce pyroxene. The Cerro Puntudo consists of dacite characterized by an agglomerate of plagioclase crystals and scarce amphiboles in a vitric matrix with small plagioclase microlites. The two samples of Cerro and Sierra Chorreada are characterized by andesites with hornblende and abundant pyroxenes in a vitric matrix. The Cerro Plateado exhumed volcano is represented by dacites with similar characteristics than the Cerro Puntudo, but the matrix is hyalopilitic. The Cerro Diamante andesite belongs to a volcanic remnant of the basement of the Quaternary volcano. The geographic coordinates and the different minerals used for the K-Ar dating are indicated in the Table 1.

The selected rocks of these centers were dated by K-Ar in the Laboratory of Geochronology of the SERNAGEOMIN in Chile and the data are presented in Table 1. The areal distribution of the new ages as indicated in Fig. 2 shows that there is a wave from older rocks in the south and west that are becoming younger to the north and east. For example in Sierra de Huantraico the oldest ages are between 18 and 16 Ma, that become slightly younger in the El Zaino Volcano (13.7 Ma), in El Puntudo Volcano (11.4 Ma), in Sierra Chorreada (11.3 Ma), north of El Sosneado (10.7 Ma) and at the base in the old edifice of Cerro Diamante (7.38 Ma). A similar trend is observed in the easternmost calcalkaline volcanic centers, where southeast of Cerro Diamante, Los Cerritos has 7.4 Ma, Plateado Volcano 3.9 Ma, and Sierra de Chachahuén centers vary from 7.3 to 4.8 Ma.

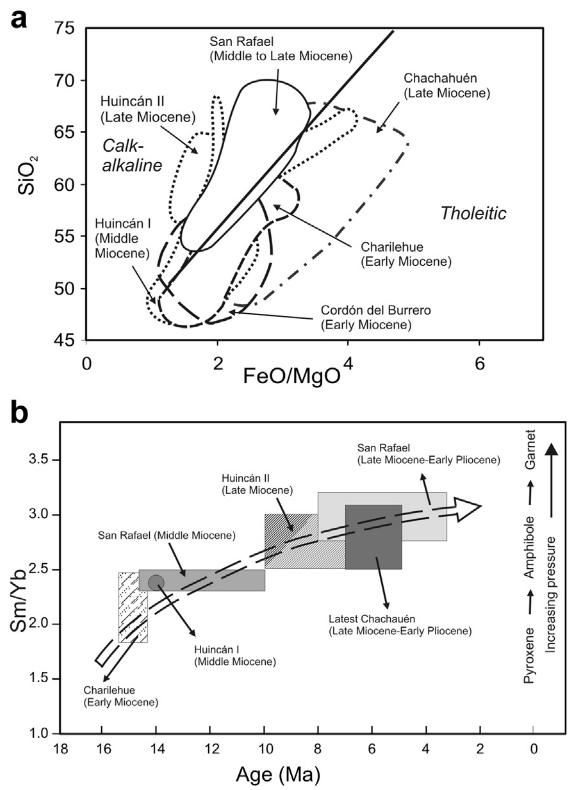

Figure 4. (a) SiO_2 vs. FeO/MgO diagrams evidence a tholeiitic signature for older Miocene lavas relatively to younger ones from upper Miocene age; (b) Sm/Yb relation as a function of age. Early Miocene Chariluehe magmas appear to have been equilibrated in a thinner crust than younger Miocene–Pliocene sequences, as reflected in its lowest Sm/Yb ratios, while San Rafael and part of Chachahuén rocks have the highest Sm/Yb ratios of the whole trend (modified from Spagnuolo et al., 2012a). Data from Huincan I, II, Chachahuén, Charilehue, San Rafael and Cerro Negro correspond to Nullo et al. (2002), Kay et al. (2006a, b), Litvak et al. (2008, 2009) and Spagnuolo et al. (2012a).

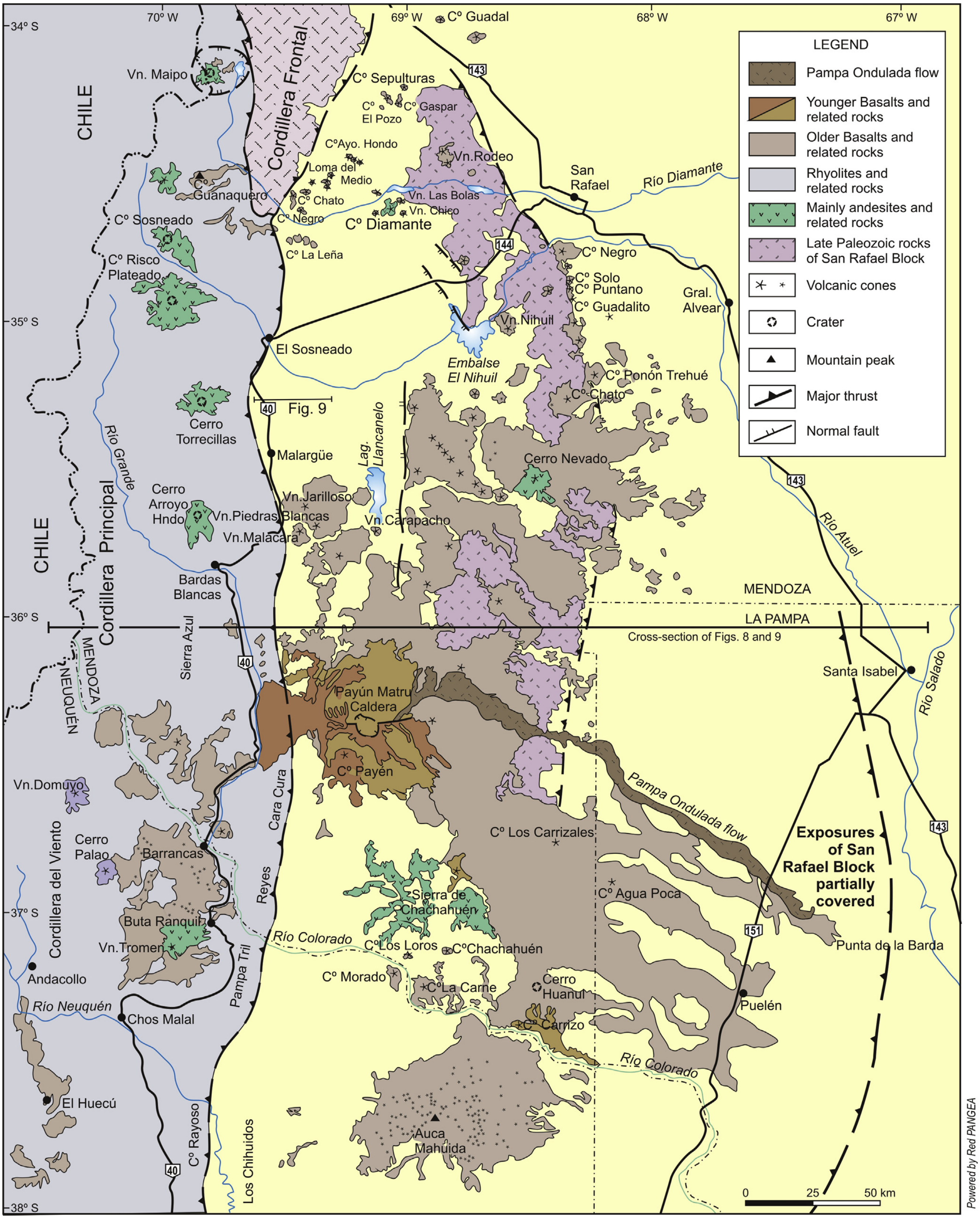

Figure 5. Distribution of the Payenia basaltic province and associated basaltic volcanic districts (modified from Ramos and Folguera, 2011).

The age pattern resembles the variations observed further north in the Pampean flat-slab where a younging in volcanic activity is detected from north to south and from west to east during the shallowing of the subduction zone (Kay et al., 1991; Ramos et al., 2002). In the Payenia volcanic rocks the pattern has a south to north polarity, looking as if the shallowing have varied from the south to the north, and from the west to the east, ranging in age from 18 Ma in Sierra de Huantraico to 7.38 Ma in Cerro Diamante, reaching the youngest ages in Cerro Plateado with 3.9 Ma (see Fig. 2 and Table 1). The only exceptional sample belongs to the Cerro Peceño, which is much younger and probably correspond to a small crustal melt emplaced during the last volcanic episodes.

3.1.2. Main geochemical features

Middle to late Miocene magmas in the retroarc show chemical signatures that are consistent with subducted components influenced by a mantle wedge above a subducting slab (Nullo et al., 2002; Kay et al., 2006a, b; Litvak et al., 2008, 2009; Spagnuolo et al., 2012a). This calcalkaline retroarc volcanism can be included in two main volcanic stages, related not only to age but also to geochemical character of the rock units. The first from 10 to 15 Ma, middle to late Miocene volcanic rocks, show basaltic and andesitic to dacitic compositions and relatively weak arc signatures; the second from 8 to 3.5 Ma, latest Miocene to early Pliocene age, shows an increase of typical arc-related chemical signature with stronger evidence of a subducted slab component.

Major element composition for the entire middle to late Miocene calc-alkaline sequences show that older lavas, such as the Charilehue volcanics and the first stages of Chachahuén Volcanic Complex show arc-related chemical signature weaker than the younger volcanism, evidenced for example by a tholeiitic-related response in the SiO_2 vs. FeO/MgO diagram (Fig. 4a). This is consistent with lower Miocene volcanism in Sierra de Huatrainco, located further southwest of Chachahuén Volcanic Complex (Fig. 2). These lavas change from basaltic to trachyandesitic composition, with back-arc chemical features and a weak but temporally increasing arc geochemical signature, and a more depleted isotopic behavior than observed elsewhere in the Andean back-arc (Dyhr et al., 2013).

In contrast, younger volcanic rocks represented here by the middle to upper Miocene stratovolcanoes previously reported, show major element ratios with a clear arc-related signature relative to the weaker pattern of Charilehue and earlier Miocene sequences (Litvak et al., 2008, 2009; Spagnuolo et al., 2012a).

The calcalkaline sequence evidences the arc-like source from their trace element mantle normalized diagrams, which show depletion of HFSE relative to LILE, as a result of subducted slab components contribution (Kay et al., 2006a, b; Litvak et al., 2008, 2009; Spagnuolo et al., 2012a). However, as reported by Kay et al. (2006a) differences in the Ba/La, La/Ta and Ta/Hf ratios between early and late Miocene lavas also display increase in arc-like signatures from older to younger volcanism.

Chemical signature of the lavas changed in late Miocene when considering Sm/Yb and La/Yb ratios as depth-indicators. The concave-up normalized REE diagrams for the calcalkaline magmas evidence pyroxene and amphibole crystallization as residual mineral assemblages in equilibrium with magmas at depth. However, there is an increase in these ratios from middle to late Miocene that indicates an increase in pressure condition in the fluids source (Fig. 4b) (Baldauf, 1997; Nullo et al., 2002; Kay et al., 2006a, b; Litvak et al., 2008, 2009; Spagnuolo et al., 2012a). The main difference in the evolution of the Miocene volcanic arc is seen during the latest Miocene–early Pliocene and reflected in the geochemistry of Chachahuén Volcanic Complex and younger San Rafael volcanism, which shows the higher Sm/Yb ratios and a more classical arc related behavior (Litvak et al., 2010). In contrast, Charilehue sequence shows a tholeiitic signature and the lowest Sm/Yb ratios in the region compared to previous and younger arc rocks (Spagnuolo et al., 2012a). Overall, middle to late Miocene volcanism of southern Mendoza and northern Neuquén shows a concomitant increase in depth of magma source, probably related to an increase in crustal thickness as a result of the shallowing of the subducted slab (Fig. 4b) (Nullo et al., 2002; Kay et al., 2006a, b).

3.2. The Quaternary foreland basalts

Most of the foreland area where the expansion of the calcalkaline rocks took place was later covered by an important basaltic plateau. These arc rocks are preserved as remnants partially or completely covered by younger basalts. The low viscosity of these magmas has produced peculiar long lava flows, extending as far as 180 km from their vent source, being one of the longest known individual Quaternary lava flow on Earth (Pasquaré et al., 2008). Chemistry of this lava flow (Pampa Ondulada flow, Fig. 5) suggests that magmatism of the Payenia Volcanic Complex mainly belongs to the Na-alkaline series and is prevailingly constituted by basaltic rocks ranging from hawaiites to slightly sub-alkaline basalts and more evolved magmas, up to trachytic compositions (Pasquaré et al., 2008).

Based on the geochemical affinities of the whole foreland basaltic plateau (Fig. 1) three main assemblages can be recognized: basalts from a northern, central and southern zone (Bertotto et al., 2009; Llambías et al., 2010). Major elements show that most of the rocks are classified as trachybasalts, basalts, and basanites and plot

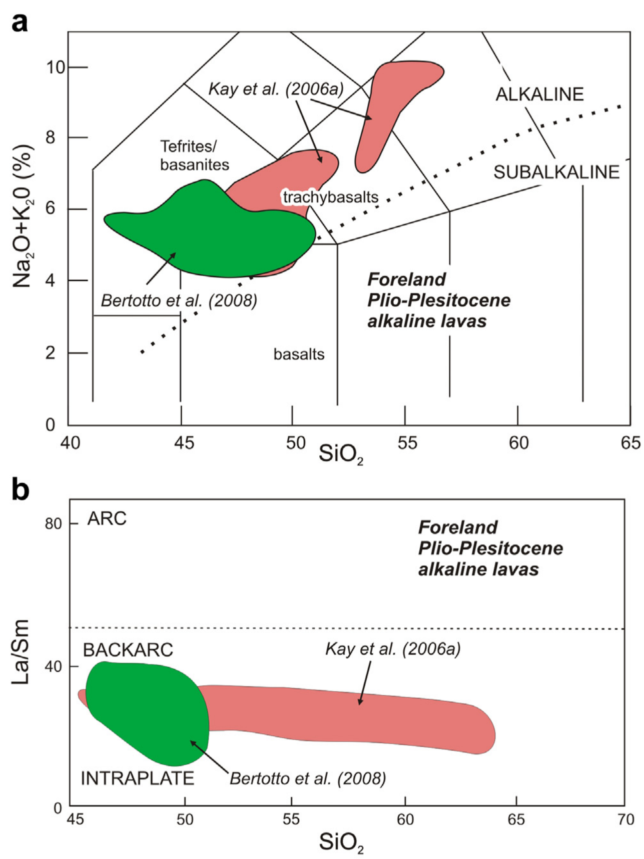

Figure 6. (a) TAS classification diagram and division of Irvine and Baragar (1971) of alkaline and subalkaline fields, for the Plio-Pleistocene foreland basalts sequences; (b) La/Sm vs. SiO_2 diagram evidence the intraplate affinity of the volcanism. Data after Llambías et al. (2010, and references therein).

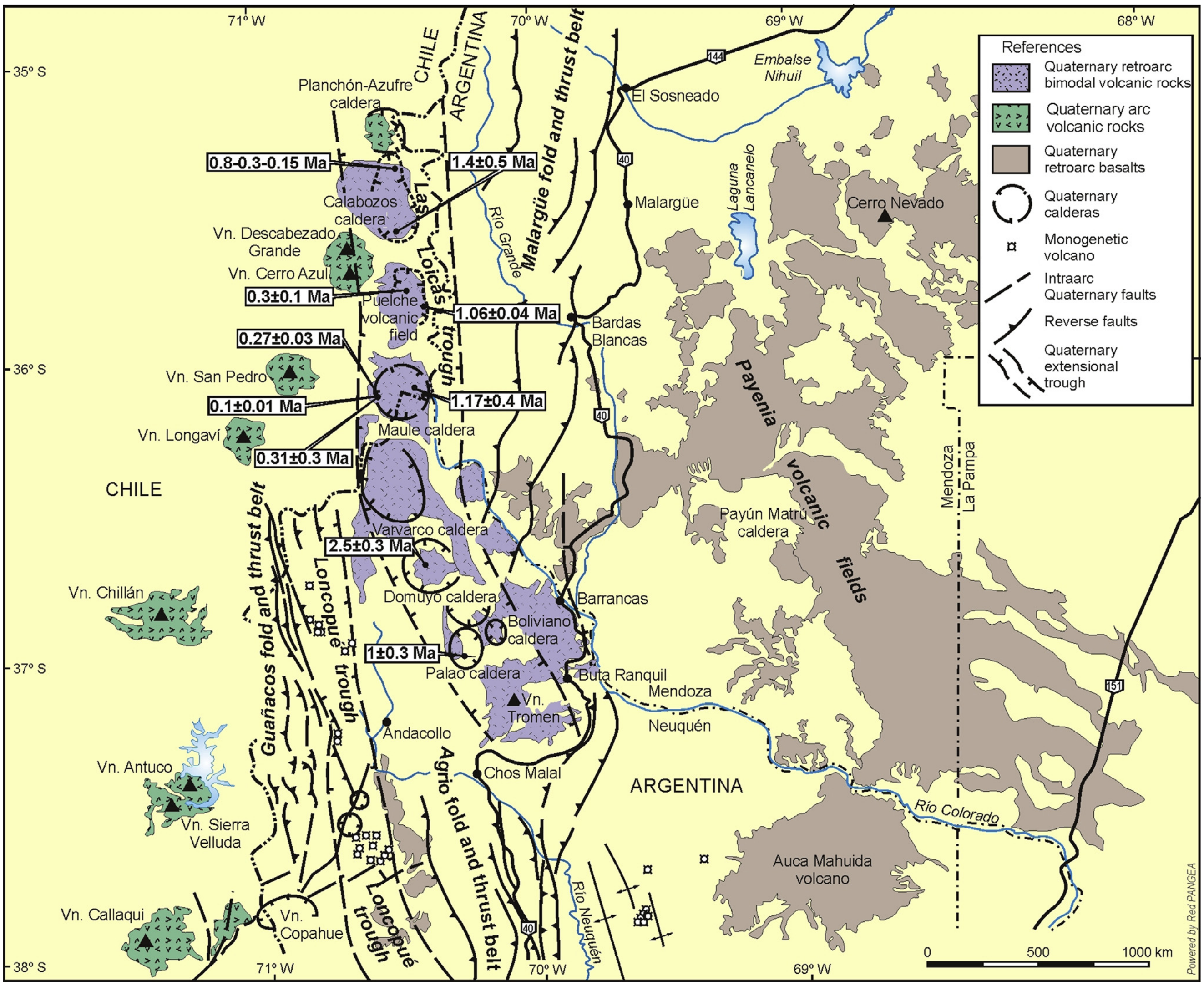

Figure 7. Main volcanic features along the Main Andes. Note the extensionally controlled Las Loicas and Loncopué troughs, where rhyolitic calderas, large rhyolitic fields, and rhyolitic domes are emplaced (based on Hildreth et al., 1991, 1998; Folguera et al., 2010).

within the alkaline field considering alkalis vs. silica diagram (Fig. 6a). However, trace elements and rare earth signature show particular differences considering age and geographical distribution of the lavas. Basalts form the northern zone, which are closer to the arc-stratovolcanoes (such as Cerros Nevado, Plateado, Pelado) according to Bertotto et al. (2009) show an enrichment in incompatible elements, strong Nb-Ta anomalies and an overall pattern with features similar to those basalts from the volcanic arc; rocks from the central zone show concentrations similar to those of the transitional basalts with some tendency towards the cratonic within plate field, whereas samples from the southern zone have patterns similar to the transitional basalts from Patagonia. In the northern zone there is also an age correlation: older Miocene basalts do not show significant arc influence such as the Plio-Pleistocene rocks from the same area. Bertotto et al. (2009) mentioned that Nb/Zr and Nb/Y ratios and rare earth patterns of the whole basalts indicate low degree of partial melting of an enriched mantle as source of these lavas, but conclude that these primary melts were modified by subduction-related fluids, particularly in the northern zone, consistent with north and eastward migration of the slab fluid metasomatism in response to an episode of sub-horizontal subduction during upper Miocene, as proposed by Kay et al. (2006a, b).

As pointed out by Llambías et al. (2010), a similar situation is reported in the area near El Nevado volcano, where Pliocene–Pleistocene alkaline basalts show low incompatible element concentration, low Nd and high Sr and Pb isotopic ratios and strong arc affinity, whereas modern basalts have higher incompatible element concentration, high Nd and low Sr and Pb ratios and a weak arc signature (Saal et al., 1995). A general increase of the alkaline character with time seems to be occurred (Pasquaré et al., 2008).

In agreement, Kay et al. (2006b) reported chemical features of the mafic lavas of Pliocene to Pleistocene age of the region, including also the voluminous latest Pliocene to Pleistocene lavas of the Auca Mahuida, Payún Matrú, and Llancanelo fields (Fig. 5). They are olivine-bearing alkali basalts, hawaiites, benmorites, trachyandesites, and trachytes characterized by intraplate La/Ta and Ta/Hf ratios and transitional arc-like Ba/La ratios (Fig. 6b). They suggest that the strongly intraplate chemistry of the Auca Mahuida and southern Payún Matrú flows, the younger lavas of the sequence, is consistent with an intraplate mantle source over a steep subduction zone; concluding that the source of Pleistocene–Holocene magmas in the retroarc corresponds to a 4–10% degree of melting of a mantle that was previously hydrated during a period of sub-horizontal subduction.

Recent studies of Søager et al. (2013) established an important difference between the northern and southern Payenia basalts. Those exposed south of the Río Diamante (see location in Fig. 5) are alkaline intraplate basalts sourced by an EM-1 OIB-like mantle while those from the Tromen volcanic plateau are basalts that have had no to very little input from the subducting slab. On the other hand those north of Río Diamante are ordinary backarc basalts formed by addition of fluids and melts from the subducting slab to a more MORB-like mantle source which was probably not hotter than average MORB mantle (Søager et al., 2013).

3.3. The Quaternary rhyolitic calderas

Along the main Andes in the Southern Volcanic Zone there are at least, 60 historically and potentially active stratovolcanoes (Stern, 2004) and a series of giant silicic caldera systems and ignimbritic flows (Hildreth et al., 1984; Muñoz and Stern, 1988; Sruoga et al., 2005). The development of these large calderas, located to the east of the arc front, broadly coincides with the central latitudes of the Payenia volcanic fields in the retroarc as previously noticed by Bermúdez et al. (1993) (Fig. 7).

A major aspect in this segment of the Main Andes is the occurrence of N–NE-trending intra-arc extensional basins described between 35° and 39°S by Muñoz and Stern (1988). One of the largest basins bounded by normal faults is Las Loicas trough (Folguera et al., 2006). These extensional features have an *en-echelon* pattern, as seen in the Loncopué trough (Ramos and Folguera, 2005; Folguera et al., 2010; Rojas Vera et al., 2011), which has a similar trend, but is located further south (Fig. 7).

The Las Loicas trough is east-bounded by the Río Grande Valley and it almost coincides with the international boundary between Argentina and Chile. Large volumes of rhyolites were erupted in Pleistocene to Recent times along its axis in several volcanic fields such as the Planchón-Azufre (Naranjo and Haller, 2002; Haller and Risso, 2011), the large Calabozos caldera (Hildreth et al., 1984), the Descabezado Grande (also known as Quizapu) and Cerro Azul volcanic fields (Hildreth and Drake, 1992), Puelche volcanic field (Hildreth et al., 1999), Laguna del Maule volcanic centers (Frey et al., 1984; Hildreth et al., 2010), Varvarco caldera (Folguera et al., 2006), Domuyo center and related domes such as the Palao dome (Llambías et al., 1978; Miranda et al., 2006), and the Tromen volcanic field (Kay et al., 2006b), among others.

Three of these volcanic areas, the Puelche volcanic field, the Calabozos caldera, and the Domuyo volcanic complex are characterized by ∼1–0.1 Ma rhyolitic domes, followed by mafic eruptions with slight differences among them regarding the duration of these episodes. In contrast, the Maule volcanic field is characterized by a large caldera formed at ∼0.950 Ma associated with an almost continuous bimodal activity until 0.38 Ma through more than 150 vents (Hildreth et al., 2010). The Tromen volcanic field, with predominance of andesitic to rhyolitic products has also similar characteristics (Kay et al., 2006a, b; Galland et al., 2008).

Rhyodacitic to dacitic ash-flow sheets emplaced at 0.8, 0.3, and 0.15 Ma respectively constitute the initial stage of the Calabozos caldera (Hildreth et al., 1984), with eruptions over 1000 km^3 (Grunder and Mahood, 1988), followed by repeated caldera collapses (Grunder et al., 1987). Postcaldera eruptions have persisted up to Holocene times with dacites and andesites. Andesite piles erupted at 1.1 and 0.3 Ma constitute the basement of the Descabezado Grande volcanic complex (Hildreth and Drake, 1992). The main Quizapu volcano erupted >9.5 km^3 of rhyolitic tephra, the largest explosive eruption of any Andean volcano in the 20th century (Hildreth and Drake, 1992). Many of these ignimbritic flows cover the valleys of the Argentine slope between Malargüe and Bardas Blancas, almost reaching the plains at the foothills near the town of Malargüe (González Bonorino, 1944).

The Puelche volcanic field is a bimodal complex that has been erupted between 0.35 and 0.2 Ma (Hildreth et al., 1999) over a 1.4 ± 0.5 Ma rhyodacitic intrusion. Less than 0.10 Ma basaltic andesites are the younger products erupted in this complex.

The Maule volcanic field, located about 30 km east of the Present volcanic front represented by the Tatara-San Pedro Volcano (Dungan et al., 2001), has erupted more than 350 km^3 since the last 1.5 Ma. The Maule activity can be divided in two stages: one from 3.7 to 1.3 Ma when silicic eruptions were exclusive and second one up to postglacial times when a bimodal activity took place (Hildreth et al., 2010). The silicic eruptions spanned in four pulses from 3.7 Ma to 1.24 Ma, and the mafic stratovolcanoes are younger than 1.3 Ma. A large 550 m thick ignimbrite dated at 0.937 ± 0.04 Ma poured over the region related to the caldera collapse (Hildreth et al., 2010). Since then silicic eruptions were continuous up to 23 Ka in postglacial times, coexisting with mafic lavas (Singer et al., 2000).

The Domuyo volcanic complex started with the emplacement of a presently highly eroded 2.5 ± 0.5 Ma rhyolitic body. Rhyolitic domes between 0.720 and 0.110 Ma were emplaced surrounding the central body (Miranda et al., 2006). An ignimbritic sheet preceded the emplacement of the older domes. Less than 0.10 Ma mafic flows complete the evolution of the Domuyo complex. NE and E normal faults associated with the emplacement of the acid domes affect the basement of this volcanic complex.

The Tromen volcanic center is formed by a mafic plateau of 2.27 to 1.8 Ma, over which an ignimbrite eruption at about 1.96 Ma took place (Galland et al., 2008). The young volcanic field is characterized by bimodal activity between 1.45 and 0.75 Ma, with an increasing tendency to the production of small stratovolcanoes. In the last 0.20 Ma stratovolcano construction associated with mafic eruptions was again the predominant eruptive mechanism (Kay et al., 2006a; Folguera et al., 2007; Galland et al., 2008). This complex is associated with N-trending grabens and halfgrabens gathered in the La Amarga extensional system that controlled the emplacement of the 2–1.8 Ma lava products, and a later stage after 0.9 Ma.

The Diamante Caldera that hosts the Maipo resurgent volcano (see location in Fig. 5) is the northernmost silicic caldera that erupted 270–350 km^3 of rhyolitic, non- to moderately welded ignimbrites (Guerstein, 1990). The caldera has been dated in 0.450 Ma and its tephras are known as the *Asociación Piroclástica Pumícea* in the Argentine plains (Polanski, 1963) and Diamante Tuff (Harrington, 1989), that extends widely in Chile and Argentina and covers an area of 23,000 km^2 (Stern et al., 1984). The Maipo volcano is represented by several eruptive episodes ranging from 0.086 to 0.014 Ma, and also encompasses some historical eruptions (Sruoga et al., 2005).

The Loncopué trough is further south and parallel to Las Loicas (Muñoz and Stern, 1988; Melnick et al., 2006). It contains several caldera systems along its western boundary such as the Agrio, Nuco Pehuén and Chuenque Pehué calderas (Rojas Vera et al., 2011). Those erupted ignimbrites are dated at 2 Ma and controlled the emplacement of large silicic domes (Linares et al., 1999). However, the Loncopué extensional basin is dominated by monogenetic Quaternary scoria and lava cones of basaltic composition along its axial part as described by Rojas Vera et al. (2010, 2011).

An interesting feature within this pattern of rhyolitic rocks and calderas east of the Present main arc is the Cerro Peceño, south of the Nihuil Lake (see location in Fig. 2). This center is the only rhyolitic vent located in the middle of the Payenia basaltic province, outside of the Payún Matrú caldera (Llambías et al., 2010). It is composed of rhyolitic lavas and ignimbritic welded tuffs, very well

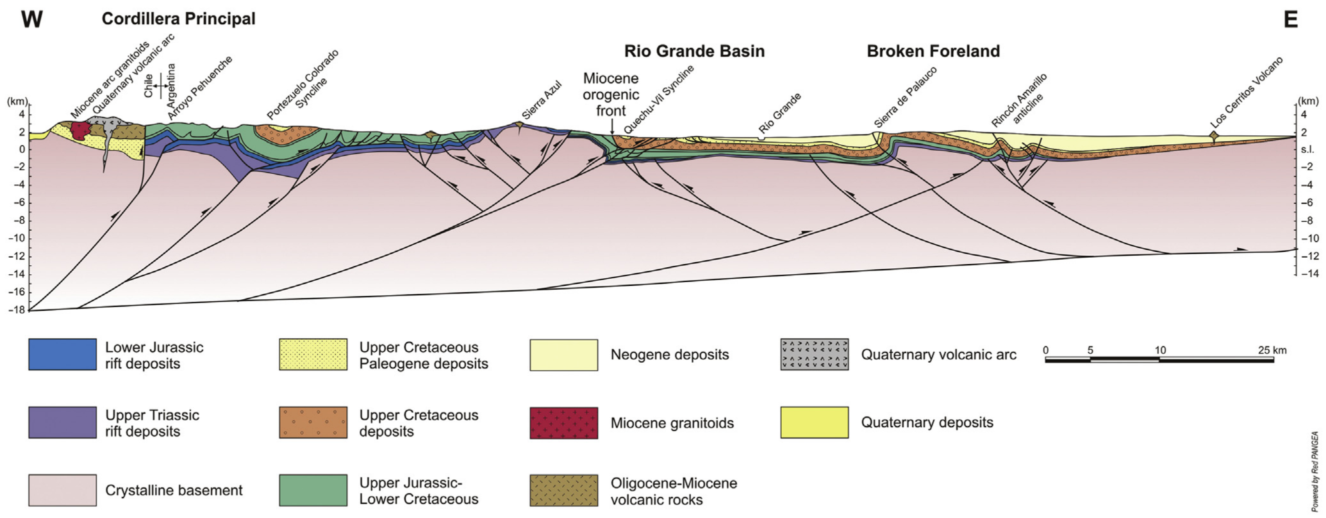

Figure 8. Regional structural section across the study area showing the Cordillera Principal, the foothill structures, and the related Miocene arc volcanic rocks (based on Orts et al., 2012; Giambiagi et al., 2009, 2012, and field observations of the authors). See location in Fig. 5.

preserved with some ash-fall tuffs interbedded, with an extent of few hundred meters around a small dome. Two ages have been obtained in this center with an average age of 0.8 ± 0.1 Ma (see Table 1).

It is important to remark that isotopic data along the Cordillera Principal at 35°–37°S latitudes (see Fig. 7) indicate that the generation of the rhyolitic eruptions involved significant contributions from crustal partial melts (Grunder, 1987; Stern, 2004). Stern (2004) suggested a northward increase of subduction erosion as one of the main components of the magmas, but the largest contribution is produced by melts in the deep crust as demonstrated by Hildreth and Moorbath (1988) to account for the chemical and isotopic data.

4. Magmatism and deformation

The analysis of the present structure shows the development of the Malargüe fold and thrust belt (Kozlowski et al., 1993) with the location of the thrust front of the Cordillera Principal controlled by a series of basement reverse faults along the foothills (Fig. 1). Parts of these structures have been formed by a late Cretaceous–Paleogene deformation event as identified by Orts et al. (2012) and Spagnuolo et al. (2012b). The thick late Cretaceous synorogenic deposits of the Neuquén Group are preserved in the Portezuelos Colorados syncline near the water divide with Chile (Fig. 8). Some patches of these deposits have been found in the Chilean slope by Mescua et al. (2013), which clearly indicate that the orogenic front at that time was close to the present international Argentine border, or even partially in Chile.

The folded late Cretaceous and Eocene deposits in that syncline indicate that the structure was formed during Neogene deformation. Fission track analyses in the Miocene granitoids of the Cordillera Principal in Chile, which constitute the magmatic arc front at these latitudes, show that uplift and exhumation occurred in two phases (Spikings et al., 2008). A rapid cooling at 18 and 15 Ma is attributed to both thermal relaxation following magmatic intrusion and regional-scale exhumation of the axial series of Miocene stocks (Spikings et al., 2008). However, the spatial and temporal coincidence of rapid cooling with deformation in the eastern slope of the Cordillera Principal (Orts et al., 2012), a transition from tholeiitic to calc-alkaline arc compositional trends between 18 and 14 Ma (Ramos and Kay, 2006; Sruoga et al., 2008), and a depositional hiatus, clearly show that a component of cooling was also driven by tectonic exhumation that was coeval with crustal thickening. The onset of elevated exhumation rates during the late Miocene between c. 10 Ma and c. 7.5 Ma in the Cordillera Principal is related to the expansion of the deformation to the foreland.

The Pampa Palauco anticline was the first structure uplifted in the foreland (Fig. 8) between 11 and 8 Ma (Silvestro and Atencio, 2009), in coincidence with the period of elevated exhumation in the Cordillera Principal in Chile. At that time a rapid expansion of the calcalkaline suites in the foreland was recorded, where the andesites and dacites of the Cerros El Zaino (13.7 ± 0.8 Ma), Puntudo (11.1 ± 0.6 Ma), Chorreado (11.2 ± 1.3 Ma), Plateado (3.9 ± 0.4 Ma) and Los Cerritos (7.4 ± 0.5 Ma), and Sierra Chorreada (11.3 ± 1.0 Ma) were erupted (see Table 1) several kilometers to the east of the volcanic front.

Subsequent deformation expanded between 8 and 3 Ma towards the east uplifting the Rincón Amarillo anticline and other structures in the eastern foreland. Deformation expanded further to the far foreland, uplifting the San Rafael block, and exhuming the late Miocene distal deposits by the Santa Isabel thrust in the Pampa Central (Fig. 9) as indicated by Folguera and Zárate (2009). During this interval the last calcalkaline volcanic rocks were erupted in the foreland.

The maximum expansion of the structure developed between 8 and 3 Ma according to Silvestro and Atencio (2009), was followed by a general extensional collapse (see Folguera et al., 2009) and the flooding of the huge basaltic Payenia Volcanic Complex in the foreland province (Fig. 5). The basaltic province was developed in the last two million years (Ramos and Folguera, 2011). The detailed analysis of the distribution of the basaltic province of Payenia shows a progression to the west and to the north (Folguera et al., 2009; Gudnason et al., 2012).

Monogenetic cones of basaltic composition during late Pleistocene to Holocene migrated backwards to the west and northwest, where the younger cones and minor basaltic flows are found.

The axial cordillera in the last one million years was the locus of large rhyolitic eruptions, some of them related to caldera collapses, and important magmatic activity (González-Ferrán, 1995; Fournier et al., 2010). Hildreth et al. (2010) have identified in the Maule volcanic field more than hundred separate Quaternary vents with a volume >350 km^3 of mainly rhyolitic products. INSAR (interferometric synthetic aperture radar) data indicate that the vertical uplift in the Maule volcanic field has accelerated from zero in 2004

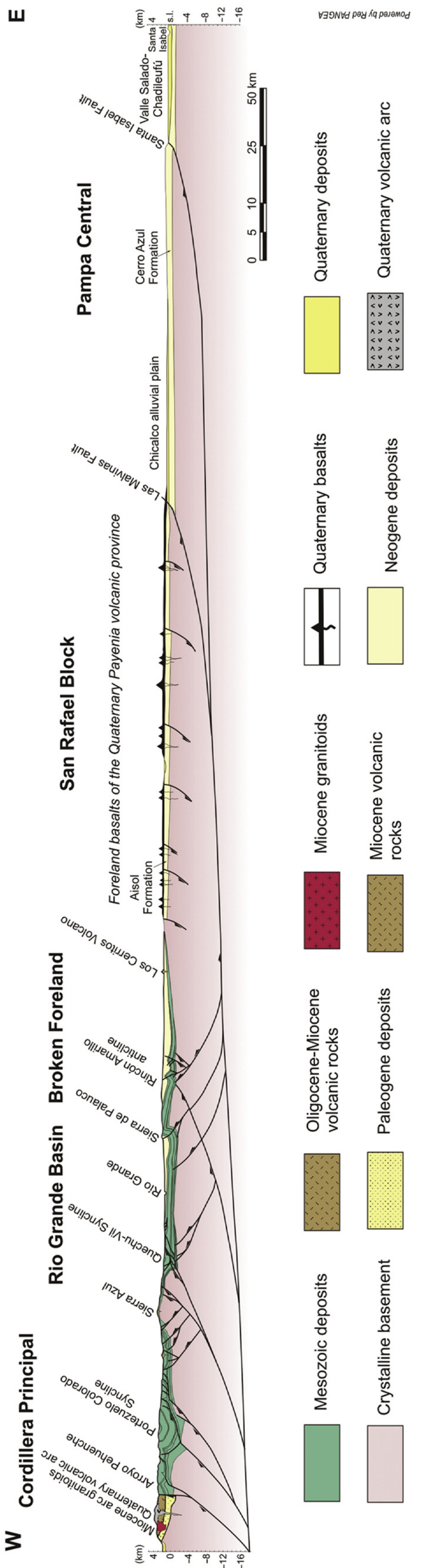

Figure 9. Regional cross-section depicting the foreland structure and associated magmatism along the San Rafael Block and Pampa Central (modified from Folguera et al., 2009 and Folguera and Zárate, 2009).

to 300 mm/yr in 2012. In total, more than 1.4 m of uplift has been recorded since 2007 (Le Mével et al., 2012), which clearly indicates how active is the emplacement of the rhyolitic products.

5. Discussion

The new ages obtained, combined with previous ages and fission track data, when integrated with the timing of the deformation and the sedimentation of synorogenic deposits show a distinctive tectonic evolution of this segment of the southern Central Andes between 34° and 37°S.

High-resolution tomographic images show large areas of the upper plate, beneath of the Payenia Volcanic Province, with large negative arrivals within the crust indicative of low rigidity of the upper crust (Gilbert et al., 2006). These negative values coincide with the region of Quaternary basaltic volcanism of Payenia. Further to the west it depicts the oceanic slab, which descends with a normal dipping 30° angle to the east (Fig. 9 of Gilbert et al., 2006).

Based on the existing and new data a series of tectonic stages can be identified from the early Miocene to the Present that are illustrated in Fig. 10.

5.1. *Early Miocene deformation (18–15 Ma)*

After the extensional period between 27 and ~19 Ma recorded by Charrier et al. (2005) in the Coya Machalí Basin along the Chilean side, a new magmatic cycle began. This cycle started in the early Miocene with the emplacement of arc granitoids and related volcanic products along the Cordillera Principal in Chile. The oldest Ar-Ar granitoid ages of Spikings et al. (2008) at these latitudes (35–38°) are 20.3 ± 0.2 Ma, although some older 24 Ma ages were previously reported (Charrier et al., 2002).

The rapid cooling at 18 and 15 Ma of the granitoids following magmatic intrusion and regional-scale exhumation was identified by fission track data (Spikings et al., 2008). The age of the synorogenic deposits at the Río Grande Basin indicates that exhumation of the granitoids coincides with the first pulse of deformation of the Malargüe fold and thrust belt in the Cordillera Principal (Fig. 10a). The oldest age of the synorogenic deposits is dated in 18.6 ± 0.3 Ma by Ar-Ar (Silvestro and Atencio, 2009). Along the eastern side of the cordillera volcanic rocks with ages as old as 20 to 19 Ma are observed, indicating an expansion of the arc volcanism (Fig. 2). High-K andesites and basalts in the northern sector, along the Cordón del Burrero (35°S), are widely distributed between 18 and 14 Ma (Sruoga et al., 2008). Further south at 37°S thick sequences of andesitic and dacitic rocks are described in the eastern slope of the Cordillera Principal. Large volumes of calcalkaline rocks of Charilehue Formation (>17–15 Ma) were erupted in the southern part of Mendoza as a southern extension of the Coya Machalí Basin. A few Ar-Ar ages near the top of a >1000 m thick sequence of andesites and andesitic tuffs yielded 14.8 ± 2.8 Ma and 14.51 ± 0.12 Ma (Spagnuolo et al., 2012a). Basaltic to trachyandesitic Sierra de Huatrainco back-arc lavas are also included within this magmatic stage, with reported ages between 20 and 17.5 Ma (K-Ar and Ar-Ar ages of Ramos and Barbieri (1989), Kay et al. (2006b) and Charlotte et al. (2013)).

The expansion of the magmatism and the foreland migration of the deformation are explained by crustal erosion by subduction (Kay et al., 2005) combined with shallowing of the subducted slab (Ramos and Kay, 2006; Spagnuolo et al., 2012a).

5.2. *Middle-Late Miocene deformation (14–7.5 Ma)*

Several authors have clearly identified a period when shallowing of the subducting Nazca Plate was dominant between 14 and 10 Ma in the Andes at these latitudes associated with an expansion

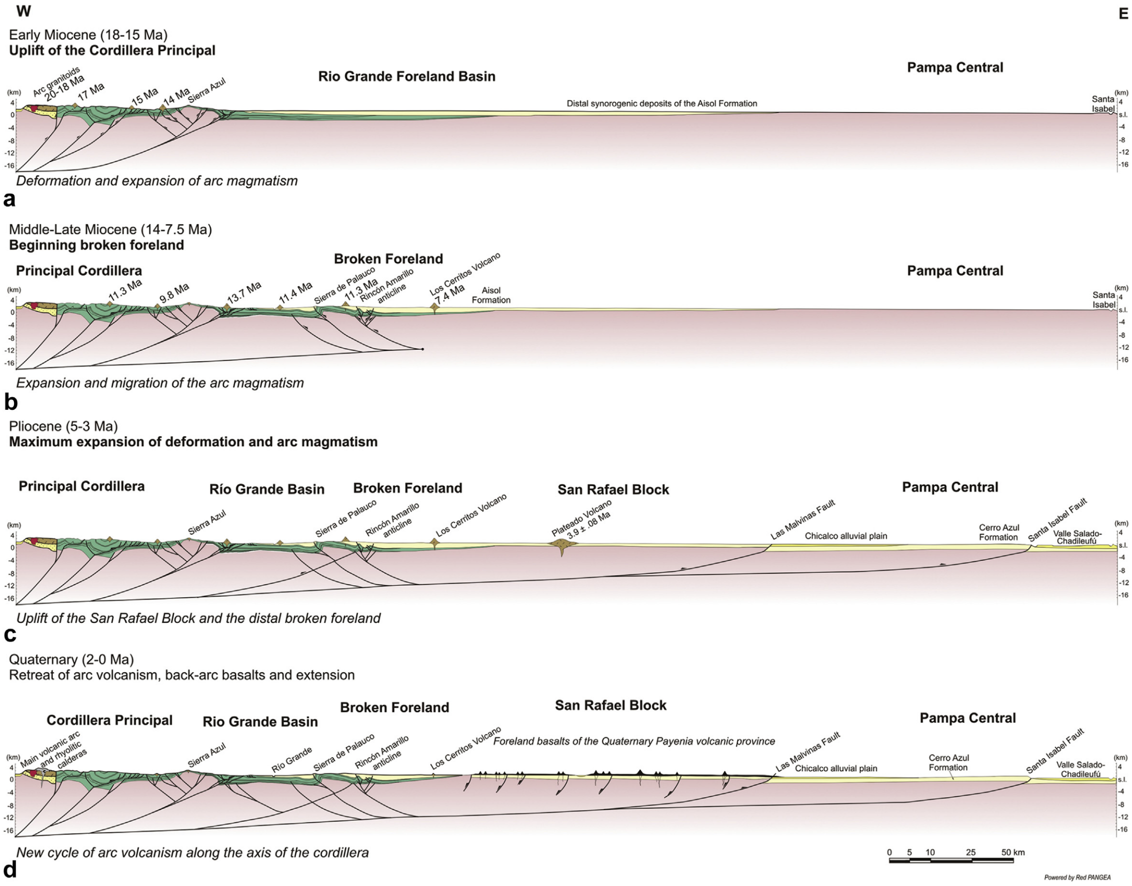

Figure 10. Geologic evolution of the Malargüe fold and thrust belt, expansion and retreat of the arc volcanism, basaltic back-arc volcanism with extension, and rhyolitic calderas and lower crustal anatexis beneath the main volcanic arc.

of the arc magmatism (Kay et al., 2006a, b; Spagnuolo et al., 2012a). The reducing subduction angle provides a driving force for compression in the upper plate via increased plate coupling. This period coincides with a rapid exhumation of the main cordillera (Spikings et al., 2008) and deformation in the present foothills (Orts et al., 2012). The fluvial deposits of the Aisol Formation exposed in the San Rafael Block and assigned to the middle to late Miocene are the distal synorogenic sediments of this uplift.

Between 13 and 7 Ma the arc volcanism rapidly expanded and migrated into the foreland, and isolated Miocene stratovolcanoes are standing in the middle of the Quaternary basaltic plains of Payenia (Fig. 10b). Uplift and deformation of the Pampa Palauco Anticline in the Sierra de Palauco (Fig. 8) took place as a response to this migration prior to 8 Ma (Kraemer and Zulliger, 1994; Giambiagi et al., 2009; Silvestro and Atencio, 2009; Alvarez Cerimedo et al., 2013).

The late Miocene coincides with the broken foreland stage as defined by Jordan (1995), when a series of east-dipping back-thrusts fragmented the foreland basement. This broken foreland characterizes the advance stage of shallowing of the oceanic slab when ceases the magmatism and the basement is contracted (Jordan et al., 1983a,b), indicating an important horizontalization of the subduction zone. The Rio Grande Basin is transported as a piggy-back basin during the uplift of the San Rafael block (Kraemer and Zulliger, 1994). Minimum arc volcanism is active after 7 Ma reduced to small and isolated vents.

5.3. Pliocene deformation (5–3 Ma)

This period corresponds to the maximum deformation in the distal broken foreland (see Figs. 8 and 9), where the Las Malvinas fault system produced the final exhumation of the San Rafael Block (Folguera et al., 2009). This exhumation is related to the maximum expansion of the arc volcanism with typical calcalkaline affinities as observed in the Plateado volcano at 3.9 $\pm$ 0.8 Ma (see Table 1). Synorogenic deposits unconformably overly the Miocene deposits in the Río Grande Basin, as well as in the San Rafael Block. The Cerro Azul Formation was deposited east of the San Rafael Block in the Pampa Central and assigned to the latest Miocene (Folguera and Zárate, 2009). The last compressional stage uplifted the basement and cannibalized these synorogenic deposits exposed in the present scarp along the Santa Isabel fault (Folguera and Zárate, 2009) (Figs. 9 and 10c) at around 3 Ma.

This period coincides with the maximum horizontalization of the subducting oceanic slab. This is represented by an arc volcanic gap and intense contractional deformation that characterize the Payenia paleoflat-slab. At that time the foreland basement was broken, and the San Rafael Block was exhumed (see the broken foreland in Fig. 8).

5.4. Pliocene to Quaternary deformation (2–0 Ma)

The maximum contraction related to the broken foreland stage during the Pliocene was followed by a general collapse of the San Rafael Block (Fig. 10d) during Quaternary times. The large Payenia Volcanic Province previously described developed in the last 2 Ma, with several basaltic monogenetic vents active during the Holocene (see details in Folguera et al., 2008; Ramos and Folguera, 2011). The basalt magmatism migrated to the north and western sectors, decreasing in volume through time.

Huge calderas and volcanic domes of rhyolitic composition and subordinate basalts were emplaced in the last one million years along the Cordillera Principal. Isolated and large stratovolcanoes were again emplaced in the western side of the Cordillera Principal during the Quaternary at these latitudes (see Fig. 1).

The basalt floods were interpreted based on their OIB composition as direct melts of the asthenosphere (Søager et al., 2013), associated with the steepening of the subducted slab during the Quaternary. The rhyolitic melts of the lower crust are here interpreted as evidence of local delamination of a narrow keel of the Cordillera Principal at these latitudes. This steepening process and its related products are still going on as inferred by the strong inflation observed in the calderas and rhyolitic domes along the Main Cordillera at 36°S.

6. Comparison with the Altiplano and Payenia paleoflat-slabs

Several studies described the geological processes related to the shallowing and steepening of the subducted slab beneath the Altiplano (Kay et al., 1999; James and Sacks, 1999; Beck and Zandt, 2002; Ramos, 2009). When these processes are compared with the Payenia paleoflat-slab, striking differences arise.

The Altiplano and the Payenia paleoflat-slabs have in common the expansion of the arc magmatism, the thickening of the crust, the wave of deformation towards the eastern foreland, and the extinction of arc volcanism along the axis of the Andean Cordillera. All these processes are related to the phase of shallowing of the oceanic subducted slab. Similar geologic facts are found in the evolution of the present Pampean flat-slab (see Ramos et al., 2002 and references therein).

The main differences are related to the lithospheric response to the steepening of the subducted slab. The hot asthenospheric injection in the Altiplano, in contact with the metasomatized lithosphere developed by previous dehydration of the slab, produced large amounts of melting (James and Sacks, 1999; Kay et al., 1999; Schurr et al., 2006). Lithospheric removal and lower crustal melts associated with the loss of the eclogitic lower crust, lead to crustal delamination (Kay and Mahlburg Kay, 1993; Kay et al., 1994; Schurr et al., 2006). All these processes resulted in melting of the lower crust and development of huge calderas and extensive rhyolitic flare-up at the surface (Lipman, 1980; de Silva, 1989, Kay and Coira, 2009).

The Payenia paleoflat-slab recorded during the steepening of the subducted slab a migration of the magmatic arc towards the trench reaching the main axis of the Andean chain similar to the Altiplano segment. However, the steepening of the slab and the injection of hot asthenosphere produced a large basaltic flooding in the retroarc, which exceeds 40,000 km^2 and more than 800 vents. This Payenia basaltic province is exceptional and unique in the entire Andean foothills. The OIB signature of these basalts (Søager et al., 2013) as well as their very low $^{87}Sr/^{86}Sr$ ratios indicates poorly evolved magmas derived directly from the hot asthenosphere. This fact was favored by the extensional regime derived from the negative trench roll-back associated with the steepening of the slab in a normal to thin crust. Thickness of the crust previous to the slab steepening was one of the major controls of the striking differences between widespread calderas and rhyolitic flare-up in the Altiplano and the basaltic floods in Payenia.

However, it is interesting to emphasize that a limited narrow belt along the Payenia segment of the southern Andes has experienced an intense rhyolitic volcanism with development of calderas in the last one million years. The segment between 34° and 37°S is the only segment of the Andes south of the Altiplano-Puna region that has acidic calderas and such an important rhyolitic flare-up. All this magmatic activity is restricted to the axial part of the cordillera, with the only exception of Cerro Peceño, a small vent of rhyolites and ignimbrites 0.8 Ma old that erupted in the middle of the foreland, along the western foothills of the San Rafael Block. We interpret that with the exception of Cerro Peceño, the calderas and the rhyolitic flare-up took place in the thickest part of the Cordillera

Principal, which at that time slightly exceeded the 42–45 km crustal thickness. Based on different petrological studies it was established that these rocks resulted by melting of the lower crust (Hildreth and Moorbath, 1988; Hildreth et al., 1999). This process is here interpreted as a minor crustal delamination that occurred only in the central and thickest part of the southern Andes in the last one million years. This delamination is still under way as inferred from the large amounts of late Pleistocene–Holocene rhyolitic vents (Hildreth et al., 2010) and the strong evidence of inflation and rapid uplift in its central part (Fournier et al., 2010; Le Mével et al., 2012).

The Payún Matru volcano and subsequent caldera are located in the middle of the retroarc foreland in the west-central Payenia Volcanic Province (Fig. 5). This region is characterized by late Pleistocene to Holocene eruptions, composed of trachytes, trachyandesites and trachybasalts. The volume of erupted material has decreased during the Holocene, probably indicating that the present thermal energy is reduced and that retroarc volcanism is ending (Germa et al., 2010; Llambías et al., 2010). These eruptions are, according to magnetotelluric studies (Burd et al., 2013), on top of a relatively deep hot spot located to at least 347 km depth in the mantle. These studies indicate that the melt feeding this hot-spot comes from the southeast to the northwest, following the trend of the entire Payenia basaltic province. This trend can be associated with two facts: (1) The shallowing of the oceanic slab from middle to late Miocene, with the older calcalkaline rocks in the southern area of the segment that became younger to the north, probably related to the subduction of an anomalous buoyant ridge. The subsequent steepening of the oceanic slab related to the ridge displacement to the north, started in the southeast corner due to the loose of buoyancy; (2) there is also a slab tear south of 38°S as suggested by Pesicek et al. (2012). This flow would be towards the northwest, as material wells up around the southern edge of the Nazca slab (Burd et al., 2013). These processes would control that the first main injection of hot asthenospheric material came from the southeastern corner of Payenia, where the steepening began.

The late Cenozoic injection of asthenospheric material in the retroarc of the Malargüe region along the Payenia Volcanic Province has some attractive consequences. Recent studies have shown that the isotopic signatures of the H_2S ($\delta^{34}S$) in the oil wells of this region range between +2.3 and +7.8‰ isotopic values, which suggests deep magmatic sources (Alberdi-Genolet et al., 2013). This H_2S is associated with a second pulse of light hydrocarbons and gas generation in the Neuquén Basin, only in southern Mendoza, in the area where we have recorded the steepening of the subducted slab and injection of hot asthenosphere beneath an attenuated lithospheric mantle.

7. Concluding remarks

Although both the Altiplano and Payenia paleoflat-slab subduction zones have similar histories, and both end with a new volcanic cycle along the main axes, it is evident that their magmatic products are entirely different. Both areas have recorded a complete orogenic cycle that begun with a volcanic arc along the cordilleran axis; expansion of the arc magmatism and deformation to the foreland; intense deformation and uplift in a broken foreland; subsequent collapse and magmatism; and final retreat of the arc volcanism to the cordilleran axis. Several segments at different latitudes along the Andes have been recognized where these cycles were formed with similar behavior (Ramos and Folguera, 2009). Furthermore, at some latitudes these cycles have been repeated, during the Paleogene and the Neogene, but with different geographic boundaries and intensity (Folguera and Ramos, 2011; Spagnuolo et al., 2012b).

These subduction cycles of shallowings and steepenings were recognized in the Central and Southern Andes (James and Sacks, 1999; Kay et al., 1999; Kay and Coira, 2009; Mamani et al., 2009; Folguera et al., 2011). However, the Payenia paleoflat-slab segment is the only one up to now characterized by intense basaltic flooding associated with the steepening of the subducted slab. Its comparison with the other cycles indicates that the original crustal thickness is controlling the existence of rhyolitic flare-ups and caldera formation, in contrast with large basaltic flooding in the foreland.

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